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Title: Current Status of Simulation-based Training in Neurosurgery: A Systematic Review

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Abstract: Objective: The recent emphasis on simulation-based training in neurosurgery has led to the development of many simulation models and training courses. We aim to identify the currently available simulators and training courses for neurosurgery, assess their validity and determine their effectiveness.

Design: Both Medline and EMBASE were searched for English language articles which validate simulation models for neurosurgery. Each study was screened according to Messick's validity framework, and rated in each domain. McGaghie's model of translational outcomes was then used to determine a level of effectiveness (LoE) for each simulator or training course.

Results: Upon screening of 6006 articles, 102 were identified either validating or determining a LoE for 97 simulation-based training models or courses. Achieving the highest rating for each validity domain were: six models and training courses for content validity; 19 for response processes; 5 for internal structure; 12 for relations to other variables and only 2 for consequences. For translational outcomes, 45 simulators or training courses were given a LoE of 1, 34 a LoE of 2, 1 a LoE of 3 and 1 a LoE of 4. Three models and one training course achieved the highest LoE of 5.

Conclusions: With the advent of increasing neurosurgery simulators and training tools, there is a need for more validity studies. Further attempts to investigate translational outcomes to the operating theatre when using these simulators is particularly warranted. Finally, more training tools incorporating full immersion simulation and non-technical skills training are recommended.

Dear Editor,

Please find submitted our systematic review on simulation-based training in neurosurgery entitled “Current Status of Simulation-based Training in Neurosurgery: A Systematic Review”. We hope it fulfils the criteria to be considered for publication in your journal. I, Abdullatif Aydin, certify that this manuscript is a unique submission and is not being considered for publication, in part or in full, with any other source in any medium.

Yours truly,

Dr. Abdullatif Aydın

*Title Page

Current Status of Simulation-based Training in Neurosurgery: A Systematic Review

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Abbreviations

ACDF: Anterior cervical discectomy and fusion

AR: Augmented Reality

CNS: Congress of neurological surgeons

CSF: Cerebrospinal fluid

ETV: Endoscopic third ventriculostomy

EVD: External Ventricular Drain

FNS: Fundamentals of neurosurgery

ICA: Internal Carotid Artery

LoE: Level of effectiveness

NET: Neuro-Endo Trainer

OSATS: Objective Structured Assessment of Technical Skills

PCF: Posterior cervical fusion

PPDIS: Physician Performance Diagnostic Inventory scale

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

SNS: Society of neurological surgeons

V-PAT: Ventriculostomy Procedural Assessment Tool

VR: Virtual Reality

Abstract

Objective: The recent emphasis on simulation-based training in neurosurgery has led to the development of many simulation models and training courses. We aim to identify the currently available simulators and training courses for neurosurgery, assess their validity and determine their effectiveness.

Design: Both Medline and EMBASE were searched for English language articles which validate simulation models for neurosurgery. Each study was screened according to Messick's validity framework, and rated in each domain. McGaghie's model of translational outcomes was then used to determine a level of effectiveness (LoE) for each simulator or training course.

Results: Upon screening of 6006 articles, 102 were identified either validating or determining a LoE for 97 simulation-based training models or courses. Achieving the highest rating for each validity domain were: six models and training courses for content validity; 19 for response processes; 5 for internal structure; 12 for relations to other variables and only 2 for consequences. For translational outcomes, 45 simulators or training courses were given a LoE of 1, 34 a LoE of 2, 1 a LoE of 3 and 1 a LoE of 4. Three models and one training course achieved the highest LoE of 5.

Conclusions: With the advent of increasing neurosurgery simulators and training tools, there is a need for more validity studies. Further attempts to investigate translational outcomes to the operating theatre when using these simulators is particularly warranted. Finally, more training tools incorporating full immersion simulation and non-technical skills training are recommended.

Introduction

Neurosurgical training has traditionally assumed the Halstedian model of ‘see one, do one, teach one’ [1]. While this model of teaching has proven invaluable over the years, it is facing increasing challenges in the modern era [2]. Issues such as cost, reduced working hours, increased expectations of patient safety, surgeon performance and transparency have led to an emphasis on protecting patients from being used as training tools themselves. The use of simulation-based training within neurosurgery has thus been advocated to enhance the current model of teaching [3]. Indeed, this mode of training has demonstrated merit for surgical skill acquisition in other specialties [4]. While many reviews exist for simulation-based training in neurosurgery, none rigorously determine the validity and effectiveness of these training models within the specialty.

The aim of this review is to identify the current simulation-based training models described in the literature, quantitatively assess their validity and determine their effectiveness for training in neurosurgery.

Methods

Information Sources and Search

A broad search of the PubMed and EMBASE databases was performed to identify articles that described neurosurgery simulators and training models. The search terms included ''neurosurgery'' and ''simulation''. Additionally, procedure specific searches were conducted including a combination of the following terms; ''ventriculostomy'', '' external ventricular drain'', ''burr hole'', ''craniotomy'', ''craniectomy'', ''ventriculo-peritoneal shunt'', ''lumbo-peritoneal shunt'', ''tumour resection'', ''dural repair'', ''laminectomy'', ''discectomy'', ''pedicle screw'' and ''neurosurgery simulation''. Titles and abstracts were screened according to the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines [5].

Study Eligibility Criteria

Original articles describing the validation and use of a neurosurgery training simulator were included. Models and simulators were then classified into the following categories: Virtual Reality (VR); Augmented Reality (AR); bench; cadaver; human tissue; and animal models. Abstracts, duplicates and non-English articles were excluded, as well as those describing the development of simulators only.

Data Extraction

Articles were first screened based on title and abstract. The remaining results were then examined, and articles were included only if they described a validation process or determined translational outcomes of the simulator.

Data Analysis

Upon selection, training models were identified and outcomes for validation studies were noted. A rating scale devised by Beckman et al. [6] was used to evaluate the strength of each source of validity evidence based on Messick's framework [7]. A level of effectiveness (LoE) was then assigned to each training model using McGaghie's proposed levels of simulation-based translational outcomes [8] (Supplementary Tables 1 and 2).

Results

Description of studies

From the 6006 articles retrieved from the search, 102 articles were identified upon screening (Figure 1). Ninety-seven simulators or simulation based training courses were either validated or had a translational outcome described (Table 1). Results were categorised into general neurosurgery; spine surgery; paediatric neurosurgery; endonasal/transsphenoidal surgery; training courses; and non-technical skills.

General neurosurgery

Overall, 47 articles validated 43 simulators for general neurosurgery (Table 2). Of these, 3 simulators were used for multiple procedures, 7 for general neurosurgery procedures, 19 for ventriculostomy, 10 for tumour resection and 19 for vascular neurosurgery.

Mixed simulators & general procedures

Three simulators for multiple procedures were validated or demonstrated a LoE in 4 articles. The remaining 7 articles described a corresponding simulator for a general neurosurgical procedure.

The S.I.M.O.N.T. was developed for training neuroendoscopy, rhinological and endonasal skull base surgery [9]. In an initial validation study, among 37 surgeons with 9 experienced, the model gained favourable responses and thus achieved a rating 1 for content, with a LoE of 1 also. The S.I.M.O.N.T. was then validated for ventriculostomy and tumour resection among 22 experienced and novice neurosurgeons [10]. A rating 2 for both internal structure and content was achieved, as retest reliability and interrater reliability were determined, and expert opinions were favourable. However, a rating 0 for relations to other variables was awarded as this was discussed, but no data was presented. Finally, a LoE of 2 was awarded as the probability of error reduced in subsequent attempts.

A perfusion-based cadaveric model was used to simulate a number of procedures within a mock operating theatre such as: extracranial-intracranial bypass; endonasal surgery with ICA injury; external ventricular drain (EVD) insertion; spinal dural repair; and endonasal surgery with CSF leak repair [11]. Trainees reported improved confidence scores for each procedure, thus demonstrating a LoE of 1. However, no validity was investigated for the model.

The MARTYN bench model was designed to train craniotomy and EVD insertion via burr holes [12]. Both realism and confidence were assessed, with an improvement demonstrated in both parameters. Thus, the model achieved a LoE of 1, and achieved a rating of 1 for content as it was assessed by 5 experts.

The ImmersiveTouch trigeminal rhizotomy simulator demonstrated a rating 2 relations to other variables among 71 residents of differing experience [13]. However, translational outcomes were not investigated in this study. A rapid-prototyped 3D model for anterior clinoidectomy was evaluated by 10 neurosurgeons, and demonstrated level 1 content [14]. However, no LoE could be determined as trainees were not surveyed. A foramen ovale puncture model achieved a rating 1 content, as five experienced neurosurgeons concluded that it mimicked the human face and was sufficient for training neurosurgeons [15]. Again, no LoE was determined in this study. Another study used the Medtronic platform with a custom 3D model, to simulate navigation, burr hole placement and frameless biopsy [16]. From 6 participants, the model demonstrated a LoE of 2. While there was difference in time and attempts between surgeon and trainees, the lack of quantitative analysis resulted in only a rating 1 for relations to other variables.

The PeriopSim™ by Conquer Mobile has two modules for burr hole surgery and instrument recognition [17]. The simulator was used to improve instrument recognition during burr hole surgery, and demonstrated a LoE of 2 as fewer errors and improved total score occurred on subsequent use. Further, performance was measured using an algorithm to calculate a total score. This earned the model a rating of 2 for response processes. USim is an app-based training approach for intra-operative ultrasound [18]. Among 14 residents, understanding and comprehension levels improved when asked to repeat the initial task, thereby demonstrating a LoE of 2 with contained effects. However, no validity was determined in this preliminary study.

A 3D-printed brain model based on MR images and designed for low cost was rated as useful for training and realistic by 10 neurosurgeons and residents [19]. The model thus earned level 1 content validity as well as a LoE of 1.

Ventriculostomy

Twelve validation studies were identified for 11 ventriculostomy simulators. Nine additional simulators for ventriculostomy are described in their respective sections. These include, two simulators for paediatric endoscopic third ventriculostomy (ETV) [20] [21], an adolescent hydrocephalus model for ETV training [22], the perfusion-based cadaveric model, MARTYN bench model and the S.I.M.O.N.T. as described earlier [11] [12] [10]. Finally, in the training course section, the Society of Neurological Surgeons (SNS) Bolivian boot camp, the Fundamentals of Neurosurgery (FNS) training module for ventriculostomy and the Congress of Neurological Surgeons (CNS) trauma module with ETV training have all been validated and are discussed accordingly [23] [24] [25].

The ImmersiveTouch, a VR simulator, was validated for EVD placement in a multicentre study involving 92 participants [26]. The simulator achieved a rating of 2 for both content and relations to other variables, however only achieved a LoE of 1.

Another group described the development of an ImmersiveTouch ventriculostomy placement task and compared it to clinical scenarios to determine how accurate the VR simulation is [27]. In the same study, the authors investigated the relationship between catheter placement and year of training, however no relationship was found. Thus a rating 0 was given for relations to other variables and no LoE was investigated in this study. The same group describe the use of the ImmersiveTouch to simulate a ventriculostomy in a shifted ventricle [28]. While no validity was determined, a LoE of 2 was demonstrated among 48 residents as a significant improvement was found on subsequent attempts. Additionally, the ImmersiveTouch was used in another study, in which the same authors describe a virtual brain library for ventriculostomy simulation [29]. Here, a rating 2 relations to other variables was achieved, and a LoE of 3 was achieved as participants were followed-up and demonstrated improved rates of first attempt catheter placement.

The introduction of simulation-based workshops using the Rowena model for EVD placement was performed as part of a quality improvement project, and led to a reduction in infection rates, increased satisfactory EVD placement rates, and reduction in displacement [30]. While validity was not investigated here, the workshops and simulator notably achieved a LoE of 4.

A hollow 3D-printed head model, designed with fast assembly and low cost, was used to simulate EVD placement for junior residents [31]. Consequences were discussed by the authors, however no data was presented to support this. A LoE of 2 was however awarded.

A 3D hydrocephalus model for teaching ETV demonstrated content validity with a rating of 1, as well as a LoE of 1 as it was assessed by 15 participants [32]. A mixed reality ventriculostomy simulator demonstrated both response processes and relations to other variables with a rating of 2 as an algorithm for timing and grading was used, and a difference between interns and residents was demonstrated, as well as a LoE of 1 [33]. A cost effective 3D model for cerebral lateral ventriculostomy training was evaluated by 10 medical students and residents, demonstrating a LoE of 1, with no validity investigated [34].

The Medtronic StealthStation, a neuronavigational tool, was used with a resin head model for ventriculostomy among 31 participants [35]. In this study, stress, performance and workload were measured earning the simulator a rating 2 for response processes, and while content was discussed, no data was presented. A LoE of 2 was also awarded as results improved with subsequent attempts.

In an initial validation study, Tai et al. demonstrated content validity (rating 1) among 4 faculty neurosurgeons as well as a LoE of 1 for a low-cost ventriculostomy simulator [36]. This model was later used with the Ventriculostomy Procedural Assessment Tool (V-PAT) and Objective Structured Assessment of Technical Skills (OSATS) and achieved rating 2 validity for all domains besides content (rating 1) among 14 participants [37]. Translational outcomes however, were not investigated.

Tumour resection

Seven simulators were validated in 10 articles for tumour resection. Three simulators are discussed elsewhere, and these include the earlier mentioned S.I.M.O.N.T. [10]. The Fundamentals of Neurosurgery also involved a tumour debulking module [24]. Finally, the skull base injectable tumour model is discussed in the endonasal surgery section [38].

Several agar-gelatin models for tumour resection of varying hardness were assessed by Mashiko et al [39]. The models demonstrated level 1 content validity among 4 neurosurgeons, and level 1 relations to other variables as they were able to discriminate between neurosurgeons and residents for tumour resection and operative time, however could not for tumour eloquent area resection. Finally, the model achieved a LoE of 2.

Formalin-fixated and latex-injected cadavers were used for a navigation-guided endoscopic intraventricular injectable tumour model [40]. The model was used to simulate endoscopic resection of an intraventricular tumour, achieving a LoE of 1, with no validity investigated.

Placenta used for simulating tumour resection demonstrated a rating 1 for content and relations to other variables due to limited expert participant number and also using only time as a measuring tool [41]. The model also achieved a LoE of 1.

An initial study on a phantom-based training system for planning tumour resection, as well as the corresponding craniotomy was assessed by 5 residents [42]. The model demonstrated a LoE of 1, however validity was not investigated. In another study among 9 participants, the same model demonstrated a rating 2 for response processes, as a standardised protocol was used to assess participants, and a rating 1 for relations to other variables as the model could distinguish between level of training for time to suture and craniotomy [43]. Additionally, improvement in time and score was demonstrated after multiple attempts and thus the model achieved a LoE of 2.

The NeuroTouch was again assessed in a study involving a meningioma-like tumour scenario [44]. Here, the simulator was given favourable responses by survey, demonstrating a LoE of 1, and when analysing performance metrics such as volume resected and duration of excessive force, the simulator achieved a rating 2 response processes, but only rating 1 for relations to other variables as it could only discriminate between students and residents, but not junior and senior residents.

The NeuroTouch glioblastoma simulation was able to differentiate between 71 medical students and 12 residents by measuring surgical effectiveness and efficiency, as well as demonstrate skill improvement among students [45]. In doing so, the simulator demonstrated relations to other variables (rating 2) and a LoE of 2.

Another group used other glioma scenarios and identified simulation metrics which assess psychomotor variables such as force applied and volume resected. These metrics were then studied using the NeuroTouch to identify proficiency benchmarks [46]. Thus the simulator was well validated achieving both relations to other variables (rating= 2) and response processes (rating=2). Translational outcomes were not investigated in this study. More complex scenarios were assessed by the same authors using the same metrics, and the NeuroTouch again demonstrated relations to other variables (rating 2), content (rating 1), response processes (rating 2) and a LoE of 1 as neurosurgeons and residents alike confirmed its usefulness for training and realism [47]. The NeuroTouch was used with the same metrics to investigate performance among 17 medical students [48]. Again, the simulator achieved rating 2 for response processes and also for relations to other variables as a difference in metric results was found between medical student deciles, as well as with residents. No LoE was investigated in the study.

Vascular neurosurgery

Twelve models were validated in 13 articles for aneurysm repair, and 3 models for general vascular neurosurgery (Table 3). Four additional models are discussed elsewhere. The earlier mentioned Perfusion-based Cadaveric model was used for extracranial-intracranial bypass and ICA injury in endonasal surgery, and is discussed in the mixed simulators section [11]. Three models for ICA injury in endonasal surgery were validated, including the adult cadaver head perfusion model [49], laser-sintered model [50], and another perfusion-based human cadaver model [51 52].

Mashiko et al. developed a series of 3D hollow elastic models, which demonstrated level 1 content, and a LoE of 1 was achieved as the models were rated favourably by junior neurosurgeons [53].

Wang et al. compared both a whole and regional 3D-printed model of cerebral aneurysm [54]. No significant difference was found between either models, however they demonstrated a rating 1 for content amongst an unspecified number of neurosurgeons, as well as achieved a LoE of 1. These models were then modified to simulate MCA aneurysm and were evaluated by 6 residents, for the tasks of planning, craniotomy and aneurysm clipping [55]. As the study involved a qualitative survey by non-experts, no validity was demonstrated, however the model did achieve a LoE of 1.

The ImmersiveTouch aneurysm clipping simulator was evaluated by 17 residents as a useful training tool, thus earning a LoE of 1 [56]. However, no validity was investigated in the study.

A virtual cerebral aneurysm-clipping model was evaluated by 18 neurosurgeons of differing experience [57]. While a survey demonstrated adequate craniotomy simulation, the clipping procedure was deemed adequate by only 22%. Overall, the model achieved content validity (rating 1) and a LoE of 1.

Human placenta was used for aneurysm clipping and was well validated among 30 participants of differing experience [58]. Indeed, the model achieved a rating 2 for each of response processes, internal structure, content and relations to other variables. Consequences was not discussed in the study, and while the participants were surveyed as to their perceived improvement in skills on using the model, this was not objectively assessed. Thus the model achieved a LoE of 1 only.

Another study investigated the use of placenta to simulate intracranial-intracranial bypass surgery [59]. The model was well validated, achieving a rating 2 for internal structure as test-retest validity was assessed among 50 healthcare professionals, rating 1 for content among 5 experts, and rating 2 for relations to other variables. No LoE was determined in the study.

Cadaver heads were compared to human placenta by another group in a later study, with human placenta demonstrating superiority for teaching sylvian fissure splitting and aneurysm dissection [60]. The study involved blinding examiners, demonstrating level 2 response processes for both models. Further, level 2 content was achieved by the placenta model as well as a LoE of 5 as use of the placenta model demonstrated satisfactory task completion during live surgery when compared to video training alone or cadaver simulation. The cadaver only achieved level 1 content as some parts of the task were not rated by the neurosurgeons and also achieved a LoE of 5, however, it should be noted that for fissure and aneurysm dissection no skill benefit was found in live surgery.

A live cadaver model with artificial aneurysms and an immersive simulation environment were used in several training courses [61]. Upon evaluation by 91 participants, the live model achieved level 2 content and a LoE of 1.

Liu et al. describe the validation of a 3D cerebral aneurysm simulator, and demonstrated level 1 content validity among 6 neurosurgeons, as well as a LoE of 1 from 4 other medical students [62].

A training program for aneurysm clipping involved practice on 3D models followed by feedback from a senior neurosurgery and a subsequent trial [63]. Trainees who had performed clipping previously demonstrated superior skill, and skill improved on subsequent trials. Overall the program achieved a LoE of 2, and demonstrated limited validity for relations to other variables due to low participant number (n=6).

Venous sinus injury with a complication of air embolus was simulated on a bench model and assessed by 12 participants [64]. Heart rate was monitored as a surrogate measure of anxiety and compared with a faculty neurosurgeon, and thus a rating 1 for both response processes and relations to other variables was awarded. A LoE of 1 was achieved as the simulator was rated favourably by trainees. The ImmersiveTouch hemostasis simulation was surveyed by 54 participants, and achieved a LoE of 1 with no validity investigated [65].

Spine surgery

Eighteen simulators for spine surgery were validated, with 5 training modules incorporated into training courses as well (Table 4).

Three simulators and training courses are discussed elsewhere. The perfusion-based cadaveric model for spinal dural repair is discussed in the mixed simulator section [11]. The CURE fellowship for spina bifida training is discussed in the paediatric neurosurgery section. Finally, the SNS fundamentals curriculum included lumbar torso drain insertion kits, and is discussed in the training program section [66].

The CNS developed 5 training modules that were incorporated into simulation courses or fellowship training. This includes a durotomy repair module used to train CSF leak repair which demonstrated a LoE of 2 among 4 participants, as improvements in mean time for closure as well as leak rate occurred [67]. However, validity was not investigated in the study. Both cervical foraminotomy and dural repair modules from a simulation course by the CNS were incorporated into a residency program at Thomas Jefferson University Hospital [68]. In doing so, the modules demonstrated a LoE of 2, as users improved in both knowledge and skills, as well as response processes (rating 2), however the modules failed relations to other variables, as no significant different in OSATS was found with advanced years of training. Additionally, the impact of microanastomosis, anterior cervical discectomy and fusion (ACDF), posterior cervical fusion (PCF), and durotomy repair modules on cognitive and technical skills was assessed with significant improvements in OSATS and knowledge [69]. This course was tested on 20 residents at the 2013 Neurological Society of India Meeting. Overall, it achieved a LoE of 2 as well as rating 2 for response processes. The anterior cervical discectomy and fusion simulator training module developed by the CNS, involved didactic teaching and use of a simulator and was assessed amongst 6 participants of varying experience [70]. An improvement in knowledge was demonstrated and thus the simulator was awarded a LoE of 2. No validity was investigated in this pilot study. The CNS also developed a cervical spine simulator for posterior foraminotomy and laminectomy, and the simulator was assessed amongst 11 participants [71]. The OSATS was used to assess technical ability, and an improvement was demonstrated after both didactic and technical components. Thus the simulation module achieved a LoE of 2, with a rating 2 for response processes.

A combined bench and virtual reality model for pedicle screw placement and lumbar stenosis decompression was evaluated by experienced spinal surgeons, using a validated questionnaire and demonstrated content validity (rating 2), with no LoE determined in the study [72].

A low cost dural repair model was used among 13 trainees, who demonstrated improved time and OSATS rating by two blinded consultant surgeons, and thus the model achieved a LoE of 2 and a rating 2 for response processes [73].

A randomized trial to assess the efficacy of a 3D software-based pedicle screw simulator was performed with subjects practising on the simulator prior to screw insertion into a cadaver [74]. From 17 respondents, the majority gave favourable responses and the simulator thus achieved a LoE of 1. It should also be noted that the subject group failed to show any improvement, and no validity was demonstrated.

A minimally invasive spine surgery model was evaluated by 8 residents and involved both animal and bench components for bilateral laminectomy training [75]. The model was given a LoE of 1 as it received favourable ratings by survey, with no validity investigated.

The Simulated Lumbar Minimally Invasive Surgery Education Model involved didactic teaching as well as use of an image-guided pedicle screw placement simulator [76]. Scores in knowledge and technical placement improved with repeated attempts, and thus the model was awarded a LoE of 2. No validity was investigated.

In a randomised trial involving 10 participants, the study group was exposed to a laboratory based spinal fixation program involving a cadaveric specimen with the Stealth S7 and Sawbones Models [77]. Both groups then performed screw placement on cadavers. Examiners were blinded, and so a rating of 2 for response processes was allocated, and a LoE of 2 was allocated as the study group produced fewer errors.

The ImmersiveTouch was used to simulate thoracic pedicle screw placement, and learning retention was then evaluated [78]. Amongst 51 participants, performance accuracy significantly improved, and the simulator was thus awarded a LoE of 2, although no validity was investigated.

The same authors then assessed the ImmersiveTouch for percutaneous spinal placement amongst 63 participants [79]. Again, an improvement in performance accuracy was demonstrated and the simulator achieved a LoE of 2, with no validity investigated.

A Saw Bones model for pedicle screw placement training in scoliosis demonstrated a rating 2 for response processes as an adapted version of the OSATS was used, however, a difference between junior and senior trainees was not found overall, but only in the domain of time and motion, thus achieving a rating 1 for relations to other variables was achieved [80]. No LoE was determined in the study.

The ImmersiveTouch was assessed for pedicle screw placement in another randomised trial involving 26 medical students [81]. Here, the simulator group demonstrated a reduced average error rate when compared to traditional teaching. Thus, the simulator demonstrated an LoE of 2, and no validity was determined in the study.

A Desktop-based computer assisted orthopaedic training system for pedicle screw insertion was assessed among 12 participants [82]. While the authors claimed their scoring system was validated among 6 experts, no data was presented, however examiners were blinded and thus a rating 2 for response processes, and rating 0 for internal structure was allocated. Mean score improved with training and thus a LoE of 2 was achieved.

A Life-Sized 3D Spine Model for pedicle screw training demonstrated a learning effect and thus achieved a LoE of 2 as placement accuracy and time both improved amongst 2 novice surgeons [83]. No validity was determined in the study.

Bioskills training modules involving sawbone models were used to train both lumbar pedicle screw placement [84] and lumbar laminectomy [85] by the same group and assessed in a randomised trial. Both studies described the use of the OSATS, and the PPDIS and thus a rating 2 for response processes was achieved. It should be noted that while both modules achieved a LoE of 2 as knowledge improved, only the lumbar laminectomy module demonstrated superior OSATS and thus skills when compared to controls.

An immersive artificial wetlab training system for lumbar discectomy was described by Adermann et al [86] and achieved a rating 1 for content among 17 spinal surgeons, as only the realism and haptic element was validated. An adapted form of the OSATS was referred to but not detailed, and thus a rating 1 for response processes was allocated. A LoE of 1 was also allocated to the model.

One study compared 3 types of cadavers, embalmed with either the Thiel method, the Crosado method, or with formaldehyde [87]. Here, the Thiel cadaver rated the highest, and the formaldehyde the lowest, and as the surgeons provided a favourable rating for cadaver use in spinal surgery simulation, a rating 1 for content was allocated. The cadavers also achieved a LoE of 1.

The virtual surgical training system for cervical pedicle screw placement training was assessed, and when compared with controls, use of the virtual system led to more accurate insertion of the pedicle screw [88]. Thus a LoE of 2 was achieved, however, no validity was determined.

A 3D patient specific rendering for pedicle screw insertion was used by 2 junior surgeons and 2 experts [89]. Here the simulator achieved a LoE of 2 as well as a rating 1 for relations to other variables as experienced surgeons performed the tasks in quicker time, and junior surgeons improved in time to complete the task.

Endonasal/transsphenoidal surgery

Fourteen articles validated 13 skull base surgery simulators (Table 5). Additionally, two simulators are discussed elsewhere. The Fundamentals of Neurosurgery course involves an endoscopic nasal navigation module and is discussed in the training course section [24]. Described in the mixed simulator section is the perfusion-based cadaveric model, used to simulate a number of procedures including endonasal surgery with ICA injury and CSF leak repair [11]. In another article, the same model was described but evaluated specifically for endoscopic endonasal CSF leak repair among 9 residents [90]. Here the model gained favourable responses by survey, and thus achieved a LoE of 1, with no validity investigated.

A 3D-printed skull base model for transnasal endoscopic skull base surgery training demonstrated some content validity (rating 1) amongst 3 experienced neurosurgeons, and achieved a LoE of 1 as 10 Residents provided favourable responses concerning the use of the model for surgical education [91].

Gagliardi et al. used the skull base injectable tumour model to train the use of the Myriad tool for endoscopic skull base procedures [38]. In this study, endonasal resection of tumours was performed by 6 surgeons, who confirmed the educational characteristics of the model by questionnaire. Overall the model achieved an LoE of 1, as well as demonstrating limited content validity (rating 1).

An adult cadaver head perfusion model was used to simulate carotid injury control using muscle graft during endonasal surgery [49]. As blood loss was reduced in subsequent sessions by learners, a LoE of 2 was achieved by the model as better management was indicated. No validity was discussed for the technical skills component of this model.

Another study validated the Neuro-Endo Trainer (NET), a part task simulator based on CT scans of patients undergoing sellar-suprasellar-parasellar endoscopic endonasal surgery [92]. The NET demonstrated level 1 relations to other variables as a statistical difference was noted between experts and novices in only a few tasks, and level 1 response processes as a Skills Assessment Scale was used. A LoE of 1 was awarded due to favourable responses post-training.

Endonasal Drilling was simulated in a bench model by Tai et al., and was tested for content amongst 8 neurosurgeons and residents. The model achieved a rating of 1, and a LoE of 1 also [93].

Drilling skills were also improved in a different study when using a chicken egg and skull model [94]. Here, a rating 2 for relations to other variables as well as a LoE of 2 was achieved among 9 participants as a difference in area removed was found to improve with successive attempts and differed from experts.

A laser-sintered model was used to simulate ICA injury during endonasal surgery and demonstrated a LoE of 2 with an improvement in skills among 46 participants [50]. However, no validity was investigated.

Another group used a perfusion-based human cadaver model for ICA injury and demonstrated a LoE of 1 as it received favourable ratings by trainees [51]. The same group attempted to demonstrate relations to other variables, however failed to do so as no difference was found between year of training or specialty [52]. In this study however, an improvement in ability was demonstrated and the model was then awarded a LoE of 2.

A practical 3D-printed simulator for basic operational skills was evaluated among 18 participants [95]. A rating 2 for relations to other variables was allocated, as significant differences in drilling, curetting and aspirating scores were achieved. Further, 5 trainees demonstrated an improvement and thus a LoE of 2 was awarded to the model.

Another study assessed the content validity of 3D skull base models with pre-existing pathology [96]. A rating 1 was awarded for content among 15 ENT surgeons of varying experience, and a LoE of 1 was achieved also. A synthetic 3D cranial base model achieved favourable responses in successive sessions from self-assessment questionnaires and thus achieved a LoE of 1 [97]. No validity was investigated in this study however.

The NeuroTouch endoscopic endonasal module was used in a randomized study to assess whether simulator use would translate to superior outcomes in the operating theatre among 6 participants [98]. The simulator achieved a rating 2 for response processes as examiners were blinded, and a LoE of 5 was awarded as participants were evaluated over a 6 month period, and demonstrated superior outcomes compared to the untrained group.

Paediatric neurosurgery

Seven simulators and 1 training course was validated for paediatric neurosurgery training in 9 articles (Table 6). Additionally, discussed in the training program section is the fundamentals curriculum which included paediatric head models by the SNS [66 99].

The babyMARTYN model was used by 18 trainee neurosurgeons for a series of procedures including, posterior fossa haematoma evacuation, pterional craniotomy, fontanelle tapping, and EVD insertion [100]. A LoE of 2 was achieved with improvement in post-training ratings and both content validity (rating 1) and response processes (rating 2) were achieved as the Physician Performance Diagnostic Inventory scale (PPDIS) was used.

A low-cost, synthetic and reusable simulator for endoscopic third ventriculostomy (ETV), called the SickKids simulator, demonstrated limited content validity among 4 neurosurgeons and 5 fellows, and achieved a LoE of 1 [20]. The SickKids simulator was then compared to The NeuroTouch simulator for ETV in a later study by Breimer et al. [21]. While both simulators demonstrated a LoE of 1 amongst 23 residents, and limited content validity (level=1) amongst 3 fellows, the authors concluded that the NeuroTouch was superior for anatomical learning whilst the bench model was superior for learning techniques and instrument familiarisation.

A full scale 3D adolescent hydrocephalus model for ETV training was evaluated by 17 subjects and demonstrated strong validity for response processes, internal structure and relations to other variables achieving a rating of 2 in each domain [22]. However, the model only achieved a LoE of 1.

The CURE Hydrocephalus and Spina Bifida fellowship combines anatomy review, web-based knowledge assessment, clinical exposure and an endoscopic simulation lab [101]. Designed for low resource settings, this fellowship demonstrated improved academic output and clinical output resulting in level 2 consequences and a LoE of 5 as changes were demonstrated in various institutions after the fellowship.

Synthetic simulators for endoscope-assisted repair of metopic and sagittal craniosynostosis were evaluated by 25 participants by survey and demonstrated a rating 1 for content as well as a LoE of 1 [102].

A Prototype model for spinal detethering surgeries demonstrated a LoE of 1 as users regarded the experience as realistic, however, despite a correlation between user experience and assigned score, no mention of a significant difference was made and thus, only a rating of 0 for relations to other variables was awarded [103].

A 3D Synthetic Model for numerous lumbar pathologies including tethered cord, fatty filum terminale, meningocele, myelomeningocele and lipomyelomeningocele was validated among 7 participants [104]. A LoE was not determined in the study, and the simulator failed to demonstrate a performance difference in skill levels based on pressure measurements. When participants were assessed by expert neurosurgeons however, a significant qualitative difference was found and thus a level 1 for relations to other variables was achieved.

Non-technical skills

An adapted Laerdal SimMan with cadaver head was used as part of a crisis management simulation involving dual neurosurgeon and anaesthetist participation (Table 4) [105]. Post-simulation surveys provided favourable responses to the simulation, demonstrating a LoE of 1, however little validity was demonstrated with level 0 achieved in relations to other variables as neurosurgeons were compared with anaesthetists with no significant difference.

A task and crisis simulator for vertebroplasty in an immersive operating theatre was rated well for training and realism, by both expert and junior neurosurgeons [106]. The VR-based simulator achieved a LoE of 1, and a rating 1 for content.

The earlier mentioned adult cadaveric head perfusion model by Ciporen et al., also assessed NTS with improved performance for situation awareness, decision making, communication, teamwork and leadership among 4 residents [49]. This earned the model a LoE of 2, and the simulator was also able to discriminate between experience of 6 residents thereby demonstrating rating 1 for relations to other variables.

Curriculum/Training Courses

Eight training courses were validated in 9 articles (Table 7). Additionally, 5 spinal surgery courses are discussed in the respective section.

The SBNS-accredited Neurosurgical Skills Workshop aimed to provide experience in positioning, burr hole creation, ventricular access, and flap formation to medical students and foundation trainees with neurosurgical trainee mentors [107]. While no validity was determined, an improvement in knowledge was demonstrated and thus a LoE of 2 was awarded.

The SNS developed a fundamentals curriculum for early trainees which involved lectures and skills stations involving various bench models such as paediatric head models, lumbar torso and drain insertion kits, and plastic craniums [66]. Overall, the curriculum was well received by faculty neurosurgeons achieving a rating 2 for content, and a LoE of 2 as knowledge levels improved after the course. Participants were then contacted 6 months later and surveyed as to their knowledge retention and course effectiveness for improving patient care [99]. Thus the curriculum achieved a LoE of 3 as downstream effects was achieved.

The SNS boot camp was expanded to Bolivia, and involved didactic teaching with simulation-based training for both beginner and intermediate procedures including; ventriculostomy, lumbar puncture, craniotomy, and dural closure [23]. Whilst no validity was determined, the boot camp achieved a LoE of 1 due to favourable responses in a post-training survey.

The Fundamentals of Neurosurgery (FNS) involves a series of training modules including ventriculostomy, endoscopic nasal navigation, tumour debulking, hemostasis, and microdissection for technical skills acquisition in neurosurgical oncology [24]. These tasks were validated among an unspecified number of surgeons, who were deemed ‘subject matter experts’. A rating 1 for content was thus awarded. No LoE was determined in the initial study.

The CNS developed a presigmoid approach model for drilling simulation, and an improvement in proficiency was found after repeated attempts at the simulator [108]. The model thus achieved a LoE of 2, however no validity was investigated.

Additionally, a trauma module involving didactic teaching followed by an ImmersiveTouch ventriculostomy simulation was evaluated by 12 residents [25]. Overall, the module achieve a rating 1 for response processes, as some evaluation measures were calculated by the VR simulator itself, and a rating 2 for relations to other variables as senior residents performed significantly better. The module also achieved a LoE of 2 as participants improved with use of the simulator and gained knowledge from the didactic component. Further, a craniotomy training model was incorporated into the trauma module and evaluated in a different study [109]. The model failed to distinguish between a junior and senior group for certain measures such as time taken, but did manage to for measures such as burr hole placement and thus achieved a rating 1 for relations to other variables. Also, a LoE of 2 was achieved as both technical skills and knowledge improved following the module.

A simulation-based curriculum with 68 exercises including spine surgery, basic skills, skull base models, and endovascular cases was evaluated by survey among 180 residents. The curriculum made use of sawbones models, the ImmersiveTouch platform and cadavers. Self-reported improvements in proficiency were significant, and thus the curriculum achieved a LoE of 1 [110].

Discussion

The present study highlights a great number of simulators within neurosurgery which have each demonstrated a variable extent of validity. No studies showed complete validity for all domains, and only 6 simulators or training programs were able to demonstrate the impact of using the simulator in the operating theatre and beyond, thus achieving levels of effectiveness greater than 2. Current data demonstrate a strong belief within the specialty that simulation tools could both supplement current training, and potentially improve patient outcomes [111 112]. The reality of such perceptions must be verified, and further studies are required to determine the 'translational outcomes' of many of the identified simulators.

With 96 simulators or training courses identified, neurosurgery employs more simulation-based training than many other specialities. Simulation in neurosurgery surpasses that of otolaryngology and orthopaedics, comparing well with urology, which may be regarded at the forefront of simulation-based training [113–115]. While an overlap between the specialties must be accounted for, as in the example of spine surgery, it is promising to see a great number of simulators that have been validated or have shown levels of effectiveness.

In particular, the creation of a Simulation Committee by the CNS, has done much to improve simulation-based training in neurosurgery [116]. However, the downstream effects of such training have been less thoroughly investigated. Indeed, none of the CNS training courses reported translational outcomes in the operating theatre and thus had limited levels of effectiveness as demonstrated in the present study. Therefore, greater efforts are needed in this respect. The SNS is another group committed to implementing simulation-based training, and notably launched a training camp in Bolivia. The CURE fellowship is another example of improving access to simulation-based training, as it provides subspecialty training in Uganda. The latter achieved the highest level of effectiveness in the review. Such programs have demonstrated the wider benefits of simulation-based training in resource-limited regions.

The use of modern definitions which recognise validity as a unitary construct enables a more rigorous assessment of the suitability of these models for training future neurosurgeons [117]. However, few studies identified actually used Messick's framework when validating the simulators. An example would be that many studies did not involve the input of experts and thus were limited in their determination of content validity, as outdated definitions were used. This is consistent with surgical simulation as a whole, in which only 6.6% of studies have been reported to use these definitions for validity assessment [118]. An emphasis must therefore be made for validation studies within neurosurgery to adopt modern validity definitions, thereby enabling a more informative appraisal of any simulators or training courses in development.

Despite a great number of simulators, there were very few for non-technical skills. Non-technical skills cover teamwork, decision making, communication and situational awareness. Indeed, demand for such training is increasing amongst neurosurgical trainees particularly when compared to senior tutors [119]. Thus, non-technical skills training will play a greater role in the future of neurosurgery, and development of further training modalities for this is necessary.

Full immersion simulation is widely regarded as an important modality for training, however the cost and maintenance of such facilities presents an obstacle to their accessibility and implementation [120]. An example of immersive simulation includes the perfusion-based cadaveric system by Zada et al. which was used in a mock operating theatre [11]. Virtual reality simulators such as the ImmersiveTouch and Neurotouch can provide a solution with ever increasing realism, including 3D technology to enable sounds of the operating theatre to be incorporated [121]. However, the limitations of tactile feedback and interaction remain and thus VR remains suitable for initial training only. Overall, incorporating different modalities combined with immersive training is recommended.

The cost of simulation-based training is well demonstrated by the simulation curriculum developed by Gasco et al. [110]. The authors mention the benefit of demonstrating translational outcomes of simulation-based training in obtaining financial support for such programs. Therefore, the benefits of investigating validity and translational outcomes are not unique to the simulator, but provide impetus for the use of simulation-based training as a whole. The advent of 3D-printing has enabled many low-cost models to be developed and such simulators have been validated [19313462]. Ultimately, the importance of having multi-modal training, balanced with the need for both high- and low- cost options, will determine the progress of simulation-based training in neurosurgery.

Limitations

Neurosurgery within the United Kingdom involves training for spinal and paediatric procedures. Despite a rigorous search, some articles may have been missed as a result of this overlap with spinal orthopaedics and paediatric surgery. Furthermore, some procedures are performed by interventional radiologists in the United Kingdom and are thus not part of the neurosurgical training program, as they are in other countries. An example would be cerebral angiography, and therefore certain simulators or training courses were omitted [122].

Conclusion

Simulation training in neurosurgery is a progressing field with an increasing number of simulation-based models being developed. While some validation of these models has been performed, there is much progress to be made, with particularly few studies investigating translational outcomes to the operating theatre and beyond. The development of various training curricula is apparent, but again, greater efforts must be made to determine the translational benefit of these courses. Finally, utilising full immersion simulation, providing cost-effective training and developing simulators for non-technical skills is also warranted.

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Table 1: An overview of the available Neurosurgery simulation models described in the literature (2000–2018). Abbreviations: VR- virtual reality, AR- augmented reality, H- high, L- low, Y- yes, N- no

Name of Model (Institution/Manufacturer)	Fidelity	Availability	Type of Model	Describing Study
Mixed Simulators & General Procedures				
S.I.M.O.N.T. Neurosurgical Endotrainer (Discipline of Neurosurgery, Escola Paulista de Medicina da Universidade Federal de São Paulo, Brasil; Pro Delphus Company)	L	Y	Bench	Filho [10] Zymberg [9]
Foramen Ovale Puncture Model (Instituto de Neurologia de Curitiba, Curitiba, Brazil)	L	Y	Bench	Almeida [15]
Custom 3D Head Models with Medtronic Platform (Division of Neurosurgery, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia)	H	Y	Bench	Waran [16]
ImmersiveTouch: Trigeminal Rhizotomy Simulator (Department of Neurosurgery, University of Illinois at Chicago, Chicago, Illinois)	H	Y	VR	Shakur [13]
Perfusion-based Cadaveric Simulation Model (Department of Neurological Surgery, Keck School of Medicine, University of Southern California, Los Angeles, California)	H	Y	Cadaver	Zada [11] Christian [90]
Modelled Anatomical Replica for Training Young Neurosurgeons 'MARTYN' (Royal College of Surgeons England)	L	Y	Bench	Craven [12]
PeriopSim™ (Conquer Mobile)	L	Y	App	Clarke [17]
USim (Camelot Biomedical Systems, Genova, Italy; Neurosurgery Department, Fondazione IRCCS Istituto Neurologico Nazionale ''C.Besta'', Milan, Italy)	L	Y	Bench/App	Perin [18]
Gelatin 3D Brain Model (Department of Mechanical Engineering, Stanford University, Stanford, California, USA)	L	Y	Bench	Ploch [19]
Rapid Prototyped 3D Anterior Clinoidectomy Model (Department of Neurosurgery, Toho University Graduate School of Medicine, Tokyo, Japan)	L	Y	Bench	Okonogi [14]
Ventriculostomy				
Low-cost Ventriculostomy simulator with V-PAT and OSATS assessment tools (Department of Learning Health Sciences, University of Michigan Medical School, Ann Arbor, Michigan, USA)	L	Y	Bench	Rooney [37] Tai [36]
University of Florida Mixed Ventriculostomy Simulator (Department of Neurological Surgery, University of Florida, Gainesville, Florida, USA)	H	Y	MR	Hooten [33]

Medtronic StealthStation w/ Resin Head Model (Victor Horsley Department of Neurosurgery, The National Hospital for Neurology and Neurosurgery, Queen Square, University College London Hospitals NHS Foundation Trust, London, United Kingdom; Medtronic, Minneapolis, MN, USA)	H	Y	Bench	Kirkman [35]
ImmersiveTouch (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Perin [26]
ImmersiveTouch: Virtual Brain Library (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA; Department of Medical Education, College of Medicine, University of Chicago, Chicago, USA)	H	Y	VR	Yudkowsky [29]
ImmersiveTouch: Ventriculostomy w/ Shifted Ventricle	H	Y	VR	Lemole [28]
ImmersiveTouch: Ventriculostomy Catheter Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Banerjee [27]
Hollow 3D Printed Head (Department of Neurosurgery, Vanderbilt University Medical Center, Nashville, Tennessee)	L	Y	Bench	Bow [31]
Simulation Workshop w/ Rowena (Victor Horsley Department of Neurosurgery, National Hospital for Neurology, Queen Square; Neurodesign Ltd.)	L	Y	Bench	Dasgupta [30]
3D Hydrocephalus Model (University of Malaya, Kuala Lumpur, Malaysia)	H	N	Bench	Waran [32]
3D Cerebral Lateral Ventriculostomy Model (Division of Neurological Surgery Barrow Neurological Institute, Phoenix, Arizona, USA)	L	Y	Bench	Ryan [34]
Vascular Neurosurgery				
Whole 3D Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	L	Y	Bench	Wang [54]
Regional 3D Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	L	Y	Bench	Wang [54]
3D Whole & Regional Middle Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	L	Y	Bench	Wang[55]
3D Cerebral aneurysm Simulator (School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China)	L	Y	Bench	Liu [62]
Live Cadaver Model (Arkansas Neuroscience Institute, St. Vincent Health System, Little Rock, Arkansas, USA)	H	Y	Cadaver	Aboud [61]
Human Placenta (Barrow Neurological Institute, St. Joseph’s Hospital and Medical Center, Phoenix,	H	Y	Human	Belykh[58], de Oliveira [60]

Arizona)			Tissue	
(Microsurgical Laboratory, Department of Surgery, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil)				
Human Cadaver (Microsurgical Laboratory, Department of Surgery, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil)	H	Y	Cadaver	de Oliveira [60]
Cerebral Aneurysm Clipping Training Program (Department of Neurosurgery, Jichi Medical University, Shimotsuke Tochigi, Japan)	L	Y	Bench	Mashiko [63]
Virtual Cerebral Aneurysm Clipping with Real Time Haptic Force Feedback Model (Department of Neurosurgery, Kepler University Hospital, Linz, Austria)	H	Y	VR	Gmeiner [57]
ImmersiveTouch: Aneurysm Clipping (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Alaraj [56]
3D Hollow Elastic Models (Medical Simulation Center, Jichi Medical University, Tochigi, Japan)	L	Y	Bench	Mashiko [53]
ImmersiveTouch: Hemostasis Simulation (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Gasco [65]
Venous Sinus Injury and Air Embolus Surgical Simulation (Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon)	H	Y	Bench	Cleary [64]
Human Placenta Model: Intracranial Bypass (Placentarium, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil; Lyerly Neurosurgical Simulation Laboratory, Baptist Medical Cente, Florida, USA)	H	Y	Human Tissue	Oliveira [59]
Tumour Resection				
Phantom-based Training System (Department of Neurosurgery, University Hospital Leipzig, Leipzig, Germany)	L	Y	Bench	Müns [42] Müns[43]
Agar-Gelatin Tumour resection Models (Department of Neurosurgery, Jichi Medical University, Shimotsuke Tochigi, Japan)	L	Y	Bench	Mashiko[39]
NeuroTouch: Glioblastoma Module (CAE Healthcare, Montreal, Quebec, Canada)	H	Y	VR	Holloway [45]
NeuroTouch: Glioma Scenarios (CAE Healthcare, Montreal, Quebec, Canada)	H	Y	VR	Alzhrani [46], Alotaibi [47] Winkler-Schwartz [48]
NeuroTouch: Meningioma-like convexity tumor (CAE Healthcare, Montreal, Quebec, Canada)	H	Y	VR	Gélinas-Phaneuf [44]
Navigation-Guided Endoscopic Intraventricular Injectable Tumor Model (Department of Neurosurgery, St. Louis University, St. Louis, Missouri, USA)	H	Y	Cadaver	Ashour [40]
Human Placenta Model (Microsurgical Laboratory, Department of Surgery, Federal University of Minas	H	Y	Human	Oliveira [41]

Gerais, Belo Horizonte, Minas Gerais, Brazil)			Tissue	
Training Courses				
National Fundamentals Curriculum (Society of Neurological Surgeons)	H	Y	Bench	Selden [66], Selden [99]
Neurosurgery Boot Camp: Bolivia (Bolivian Society for Neurosurgery; Foundation for International Education in Neurological Surgery; Solidarity Bridge; University of Massachusetts)	H	Y	Bench	Ament [23]
Fundamentals of Neurosurgery (Department of Neurology and Neurosurgery, Montreal Neurological Institute and Hospital, Brain Tumour Research Centre, McGill University, Montréal, Quebec, Canada)	H	Y	VR	Choudhury [24]
Trauma Module w/ ImmersiveTouch: Ventriculostomy (Congress of Neurological Surgeons)	H	Y	VR	Schirmer [25]
Trauma Module w/ Physical Craniotomy Model (Congress of Neurological Surgeons)	L	Y	Bench	Lobel [109]
Presigmoid Approach Simulation Module (Congress of Neurological Surgeons)	L	Y	Bench	Jabbour [108]
SBNS-accredited Neurosurgical Skills Workshop (Society of British Neurological Surgeons; The Neurology and Neurosurgery Interest Group)	L	Y	Bench	Kamel [107]
Simulation Curriculum (Division of Neurosurgery; and Division of Epidemiology & Biostatistics, University of Texas Medical Branch, Galveston, Texas, USA)	H	Y	Bench/VR/Cadaver	Gasco [110]
Durotomy Repair Module (Congress of Neurological Surgeons)	L	Y	Bench	Ghobrial [67]
Cervical Foraminotomy and Durotomy Repair Modules (Congress of Neurological Surgeons)	L	Y	Bench	Ghobrial [68]
Microanastomosis, Anterior Cervical Discectomy and Fusion (ACDF), Posterior Cervical Fusion (PCF), and Durotomy Repair Modules (Congress of Neurological Surgeons)	L	Y	Bench	Zammar [69]
Anterior Discectomy and Fusion Simulator (Congress of Neurological Surgeons)	L	Y	Bench	Ray [70]
Cervical Spine Simulator (Congress of Neurological Surgeons)	L	Y	Bench	Harrop [71]
Spine Surgery				
Mixed Reality Spine Simulator (Paediatric Neurosurgery Center, Beneficencia Portuguesa Hospital, Sao Paulo, Brazil)	H	Y	Bench/VR	Coelho [72]
Low Cost Dural Closure Simulation Model (Department of Neurosurgery, Institute of Neurological Sciences, Glasgow, UK)	L	Y	Bench	Ferguson [73]
3D Software-based Pedicle Screw Simulator (Faculty of Medicine, Orthopaedic Biomechanics Laboratory, Sunnybrook Health Sciences Centre, Toronto, Ontario, Canada)	L	Y	VR	Podolsky [74]
Simulated Lumbar Minimally Invasive Surgery Education Model (Department of Neurosurgery, Thomas	L	Y	Bench	Chitale [76]

Jefferson University Hospital, Philadelphia, Pennsylvania; Mayo Clinic, Rochester, Minnesota, USA)				
Laboratory-based Spinal Fixation Training Program (Case Western Reserve University School of Medicine; Department of Neurological Surgery; Center for Spine Health, Neurological Institute, Cleveland, Ohio)	H	Y	Bench/Cadaver	Sundar [77]
Minimally Invasive Spine Surgery Simulator (Department of Neurosurgery, University of Mississippi Medical Center, Jackson, Mississippi, USA)	H	Y	Bench/Animal	Walker [75]
ImmersiveTouch: Percutaneous Spinal Needle Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Luciano[79]
ImmersiveTouch: Thoracic Pedicle Screw Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Luciano [78]
Saw Bones Scoliosis Model (Stony Brook University Hospital, Stony Brook, USA)	L	Y	Bench	Tanner [80]
Desktop-based Computer Assisted Orthopaedic Training System (Department of Computer Sciences, University of Hull, United Kingdom; Department of Orthopaedics, Leeds Teaching Hospital NHS Trust, Leeds, United Kingdom)	L	Y	VR	Rambani [82]
Life-Sized 3D Spine Model (Department of Orthopaedic Surgery, Kangnam Sacred Heart Hospital, Hallym University College of Medicine, Seoul, South Korea)	H	N	Bench	Park [83]
Bioskills Training Module: Lumbar Pedicle Screw (Northwestern Memorial Hospital, Chicago, Illinois, USA)	H	Y	Bench	Boody [84]
Bioskills Training Module: Lumbar Laminectomy (Northwestern Memorial Hospital, Chicago, Illinois, USA)	H	Y	Bench	Boody [85]
Artificial Wetlab Training System for Lumbar Discectomy (Krankenhaus Winsen, Orthopadie, Winsen, Germany)	H	Y	Bench	Adermann [86]
Cadaveric Spinal Surgery Simulation; Thiel, Crosado and formaldehyde (Health Education Yorkshire and the Humber, University of Leeds, Leeds, United Kingdom)	H	Y	Cadaver	Tomlinson [87]
Virtual Surgical Training System (Department of Orthopaedic Surgery, Changzheng Hospital, Second Military Medical University, Shanghai, China)	H	Y	VR	Hou [88]
ImmersiveTouch: Pedicle Screw Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	H	Y	VR	Gasco [81]
3D Patient-Specific Rendering: Pedicle Screw Insertion (Department of Orthopedics, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning, China)	H	N	VR	Xiang [89]
Durotomy Repair Module (Congress of Neurological Surgeons)	L	Y	Bench	Ghobrial [67]
Cervical Foraminotomy and Durotomy Repair Modules (Congress of Neurological Surgeons)	L	Y	Bench	Ghobrial [68]

Microanastomosis, Anterior Cervical Discectomy and Fusion (ACDF), Posterior Cervical Fusion (PCF), and Durotomy Repair Modules (Congress of Neurological Surgeons)	L	Y	Bench	Zammar [69]
Anterior Discectomy and Fusion Simulator (Congress of Neurological Surgeons)	L	Y	Bench	Ray [70]
Cervical Spine Simulator (Congress of Neurological Surgeons)	L	Y	Bench	Harrop [71]
Endoscopic Endonasal Transphenoidal Surgery				
Endoscopic Endonasal Drilling Model (Department of Learning Health Sciences, University of Michigan Medical School, Ann Arbor, Michigan, USA)	L	N	Bench	Tai [93]
Chicken Eggs and Skull Model (Department of Neurosurgery, Kinki University Faculty of Medicine, Osaka, Japan)	L	Y	Bench	Okuda [94]
Laser Sintered Model (Ohio State University, Columbus, Ohio, USA)	L	Y	Bench	Maza [50]
Perfusion-Based Human Cadaveric Simulation for ICA injury (Keck School of Medicine, Los Angeles, California, United States)	H	Y	Cadaver	Shen [52] Pham [51]
Practical 3D Printed Simulator (Department of Neurosurgery, Jinling Hospital, School of Medicine, Nanjing University, China)	H	Y	Bench	Wen [95]
3D Endoscopic Skull base models w/ Pre-existing pathology (Division of Neurosurgery, Department of Surgery, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia)	L	N	Bench	Narayanan [96]
3D Cranial base model (Department of Neurological Surgery, The Ohio State University Wexner Medical Center, Columbus, Ohio, USA)	L	Y	Bench	Muto [97]
NeuroTouch Simulator: Endoscopic Endonasal Module (CAE Healthcare, Montreal, Quebec, Canada)	H	Y	VR	Thawani [98]
3D Printed Skull base for Transnasal endoscopic Skull base Surgery (Beijing Neurosurgical Institute, Beijing Tiantan Hospital, Capital Medical University, Beijing, China)	L	N	Bench	Zheng [91]
Neuro-Endo-Trainer (NET) SkullBase-Task-GraspPickPlace (Centre for Biomedical Engineering, Indian Institute of Technology Delhi, New Delhi, India)	L	Y	Bench	Singh [92]
Perfusion-based Cadaveric Simulation Model: Endoscopic Endonasal CSF Leak Repair (Department of Neurological Surgery, Keck School of Medicine, University of Southern California, Los Angeles, California)	H	Y	Cadaver	Christian [90]
Skull Base Injectable Tumor Model (Macquarie Neurosurgery, Australian School of Advanced Medicine, Macquarie University, Sydney, Australia)	L	Y	Bench	Gagliardi [38]
Adult Cadaver Head Perfusion Model (Oregon Health & Science University Body Donation Program, Portland, Oregon)	H	Y	Cadaver	Ciporen [49]

Paediatric neurosurgery				
baby Modeled Anatomical Replica for Training Young Neurosurgeons 'babyMARTYN' (Victor Horsley Department of Neurosurgery, National Hospital for Neurology and Neurosurgery, Queen Square)	L	Y	Bench	Craven [100]
SickKids brain simulator (Centre for Image Guided Innovation and Therapeutic Intervention, Toronto, Ontario, Canada)	L	Y	Bench	Breimer [20] Breimer [21]
NeuroTouch Simulator: ETV Module (CAE Healthcare, Montreal, Quebec, Canada)	H	Y	VR	Breimer[21]
Full Scale Hydrocephalus Head Model (Harvard Medical School, Boston, Massachusetts and Division of Pediatric Neurosurgery, Johns Hopkins Hospital, Baltimore, Maryland, USA)	H	N	Bench	Weinstock [22]
Synthetic Endoscope-assisted Craniosynostosis Models (Center for Image-Guided Innovation and Therapeutic Innovation, The Hospital for Sick Children, Toronto)	H	Y	Bench	Eastwood [102]
CURE Hydrocephalus and Spina Bifida Fellowship (CURE Childrens Hospital of Uganda, Mbale, Uganda)	H	Y	Bench	Dewan [101]
Prototype for Pediatric Spinal Detethering Surgeries (University of Illinois ,College of Medicine at Peoria, Peoria, IL, USA)	H	N	Bench	Bailey [103]
3D Synthetic Model for Pediatric Lumbar Spine Pathologies (Department of Neurosurgery, University of Illinois College of Medicine, USA)	L	Y	Bench	Mattei [104]
Non-Technical Skills				
Crisis Management Simulation: Dual Neurosurgery and Anaesthesia Training Experience (Anesthesiology and Perioperative Medicine, Oregon Health and Science University, Portland, Oregon, United States; Department of Neurosurgery, West Virginia University School of Medicine, Morgantown, West Virginia, United States)	H	Y	Bench	Ciporen [105]
Adult Cadaver Head Perfusion Model (Oregon Health & Science University Body Donation Program, Portland, Oregon)	H	Y	Cadaver	Ciporen [49]
Task and Crisis Vertebroplasty Simulation (Technische Universitat Munchen, Munich, Germany)	H	Y	VR	Wucherer [106]

Table 2: Validation studies on training models for General Neurosurgery. Abbreviations: LoE- Level of Effectiveness, VR- virtual reality, MR – Mixed Reality.

Model (Institution / Manufacturer)	Type of Model	Study	Validation	n	Participants Demographics	LoE
Mixed Simulators & General Procedures						
S.I.M.O.N.T. Neurosurgical Endotrainer (Discipline of Neurosurgery, Escola Paulista de Medicina da Universidade Federal de São Paulo, Brasil; Pro Delphus Company)	Bench	Zymberg (2010) [9]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	37	9 Expert Neurosurgeons 28 Novice Neurosurgeons	1
	Bench	Filho (2011) [10]	Content: 2 Response processes: N Internal structure: 2 Relations to other variables: 0 Consequences: N	22	9 Experts 13 Novices	2
Perfusion-based Cadaveric Simulation Model (Department of Neurological Surgery, Keck School of Medicine, University of Southern California, Los Angeles, California)	Cadaver	Zada (2018) [11]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	52	Residents	1
Modelled Anatomical Replica for Training Young Neurosurgeons 'MARTYN' (Royal College of Surgeons England)	Bench	Craven (2014) [12]	Content: 1 Response processes: N Internal structure N Relations to other variables: N Consequences: N	18	5 Experts 4 Intermediate 9 Novices	1
Percutaneous Trigeminal Rhizotomy Simulator (Department of Neurosurgery, University of Illinois at Chicago, Chicago, Illinois)	VR	Shakur (2015) [13]	Content: N Response processes: N Internal structure: N Relations to other variables: 2 Consequences: N	71	27 Senior Residents 44 Junior Residents	0
Rapid Prototyped 3D Anterior Clinoidectomy Model (Department of Neurosurgery, Toho University Graduate School of Medicine, Tokyo, Japan)	Bench	Okonogi (2017) [14]	Content: 1 Response processes: N Internal structure: N	10	Neurosurgeons	0

			Relations to other variables: N Consequences: N			
Foramen Ovale Puncture Model (Instituto de Neurologia de Curitiba, Curitiba, Brazil)	Bench	Almeida (2006) [15]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	5	Neurosurgeons	0
Custom 3D Head Models with Medtronic Platform (Division of Neurosurgery, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia)	Bench	Waran (2014) [16]	Content: N Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	6	2 Neurosurgeons 4 Trainees	2
PeriopSim™: Instrument Trainer & Burr Hole Surgery (Conquer Mobile)	App	Clarke (2016) [17]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 0 Consequences: N	24	18 Residents 6 Expert Neurosurgeons	2
USim (Camelot Biomedical Systems, Genova, Italy; Neurosurgery Department, Fondazione IRCCS Istituto Neurologico Nazionale ''C.Besta'', Milan, Italy)	Bench/App	Perin (2018) [18]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	14	Residents	2
Gelatin 3D Brain Model (Department of Mechanical Engineering, Stanford University, Stanford, California, USA)	Bench	Ploch (2016) [19]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	10	Neurosurgeons Residents	1
Tumour Resection						
Phantom-based Training System (Department of Neurosurgery, University Hospital Leipzig, Leipzig, Germany)	Bench	Müns (2014) [42]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	5	Residents	1

	Bench	Müns (2014) [43]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 1 Consequences: N	9	Residents	2
Agar-Gelatin Tumour resection Models (Department of Neurosurgery, Jichi Medical University, Shimotsuke Tochigi, Japan)	Bench	Mashiko (2018) [39]	Content: 1 Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	9	4 Neurosurgeons 5 Residents	2
NeuroTouch: Meningioma-like convexity tumor (CAE Healthcare, Montreal, Quebec, Canada)	VR	Gélinas-Phaneuf [44]	Content: N Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	72	44 Senior Residents 18 Junior Residents 10 Medical Students	1
NeuroTouch: Glioblastoma Module (CAE Healthcare, Montreal, Quebec, Canada)	VR	Holloway (2015) [45]	Content: 1 Response processes: N Internal structure: N Relations to other variables: 2 Consequences: N	83	12 Residents 71 Medical Students	2
NeuroTouch: Glioma Scenarios (CAE Healthcare, Montreal, Quebec, Canada)	VR	Alzhrani (2015) [46]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 2 Consequences: N	33	17 Neurosurgeons 7 Senior Residents 9 Junior Residents	0
	VR	Alotaibi (2015) [47]	Content: 1 Response processes: 2 Internal structure: N Relations to other variables: 2 Consequences: N	18	6 Neurosurgeons 12 Residents	1
	VR	Winkler-Schwartz (2016) [48]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 2	22	6 Residents 16 Medical Students	0

			Consequences: N			
Navigation-Guided Endoscopic Intraventricular Injectable Tumor Model (Department of Neurosurgery, St. Louis University, St. Louis, Missouri, USA)	Cadaver	Ashour (2016) [40]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	n/a	Trainee Neurosurgeons	1
Human Placenta Model: Tumour Resection (Microsurgical Laboratory, Department of Surgery, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil)	Human Tissue	de Oliveira (2015) [41]	Content: 1 Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	16	8 Neurosurgeons 8 Residents	1
Ventriculostomy						
Low-cost Ventriculostomy simulator (Department of Learning Health Sciences, University of Michigan Medical School, Ann Arbor, Michigan, USA)	Bench	Tai (2015) [36]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	17	4 Faculty Neurosurgeons 12 residents 1 Fellow	1
With V-PAT and OSATS assessment tools	Bench	Rooney (2015) [37]	Content: 1 Response processes: 2 Internal structure: 2 Relations to other variables: 2 Consequences: 2	14	3 Expert Neurosurgeons 11 Novice Neurosurgeons	0
Medtronic StealthStation w/ Resin Head Model (Victor Horsley Department of Neurosurgery, The National Hospital for Neurology and Neurosurgery, Queen Square, University College London Hospitals NHS Foundation Trust, London, United Kingdom; Medtronic, Minneapolis, MN, USA)	Bench	Kirkman (2015) [35]	Content: 0 Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	31	10 Experienced 11 Moderate experience 10 Novice 2 Medical Students	2
3D cerebral lateral ventriculostomy model (Division of Neurological Surgery Barrow Neurological Institute, Phoenix, Arizona, USA)	Bench	Ryan (2015) [34]	Content: N Response processes: N Internal structure: N Relations to other variables: N	10	4 Residents 6 Students	1

			Consequences: N			
3D Hydrocephalus Model (University of Malaya, Kuala Lumpur, Malaysia)	Bench	Waran (2015) [32]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	15	3 Neurosurgeons 12 Trainees	1
University of Florida Mixed Ventriculostomy Simulator (Department of Neurological Surgery, University of Florida, Gainesville, Florida, USA)	MR	Hooten (2014) [33]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 2 Consequences: N	263	120 Senior Residents 71 Junior Residents 72 Interns	1
ImmersiveTouch: Ventriculostomy w/ Shifted Ventricle	VR	Lemole (2009) [28]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	48	Residents	2
ImmersiveTouch: Ventriculostomy Catheter Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Banerjee (2007) [27]	Content: N Response processes: N Internal structure: N Relations to other variables: 0 Consequences: N	78	Residents	0
ImmersiveTouch: Virtual Brain Library (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA; Department of Medical Education, College of Medicine, University of Chicago, Chicago, USA)	VR	Yudkowsky (2013) [29]	Content: N Response processes: N Internal structure N Relations to other variables: 2 Consequences: N	16	Residents	3
Simulation Workshop w/ Rowena (Victor Horsley Department of Neurosurgery, National Hospital for Neurology, Queen Square; Neurodesign Ltd.)	Bench	Dasgupta (2018) [30]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: 0	n/a	-	4

Hollow 3D Printed Head (Department of Neurosurgery, Vanderbilt University Medical Center, Nashville, Tennessee)	Bench	Bow (2018) [31]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: 0	11	3 Interns 8 Medical Students	2
ImmersiveTouch (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Perin (2018) [26]	Content: 2 Response processes: N Internal structure: N Relations to other variables: 2 Consequences: N	92	18 Neurosurgeons 25 Junior Residents 49 Senior Residents	1

Table 3: Validation studies on training models for Vascular neurosurgery. Abbreviations: LoE- Level of Effectiveness, VR- virtual reality,

Name of Model (Institution / Manufacturer)	Type of Model	Study	Validation	n	Participants Demographics	LoE
Whole 3D Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	Bench	Wang (2017) [54]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	n/a	Neurosurgeons	1
Regional 3D Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	Bench	Wang (2017) [54]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	n/a	Neurosurgeons	1
3D Whole & Regional Middle Cerebral Aneurysm Model (Department of Neurosurgery, Beijing Tian Tan Hospital, Capital Medical University, Beijing, China)	Bench	Wang (2018) [55]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	6	Residents	1
3D Cerebral aneurysm Simulator (School of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China)	Bench	Liu (2017)[62]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	10	4 Students 6 Neurosurgeons	1

Live Cadaver Model (Arkansas Neuroscience Institute, St. Vincent Health System, Little Rock, Arkansas, USA)	Cadaver	Aboud (2015) [61]	Content: 2 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	91	27 Faculty 64 Participants	1
Human Placenta Aneurysm Model (Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, Arizona)	Human Tissue	Belykh (2017)[58]	Content: 2 Response processes: 2 Internal structure: 2 Relations to other variables: 2 Consequences: N	30	4 Students 12 Residents 4 Fellows 10 Neurosurgeons	1
(Microsurgical Laboratory, Department of Surgery, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil)	Human Tissue	de Oliveira (2018) [60]	Content: 2 Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	21	12 Neurosurgeons 9 Residents	5
Human Cadaver (Microsurgical Laboratory, Department of Surgery, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil)	Cadaver	de Oliveira (2018) [60]	Content: 1 Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	21	12 Neurosurgeons 9 Residents	5
Cerebral Aneurysm Clipping Training Program (Department of Neurosurgery, Jichi Medical University, Shimotsuke Tochigi, Japan)	Bench	Mashiko (2017) [63]	Content: N Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	7	4 Residents 2 Junior Neurosurgeons 1 Senior Neurosurgeon	2

Virtual Cerebral Aneurysm Clipping with Real Time Haptic Force Feedback Model (Department of Neurosurgery, Kepler University Hospital, Linz, Austria)	Bench	Gmeiner (2018) [57]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	18	4 Residents 14 Surgeons	1
ImmersiveTouch: Aneurysm Clipping (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Alaraj (2015) [56]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	17	Residents	1
3D Hollow Elastic Models (Medical Simulation Center, Jichi Medical University, Tochigi, Japan)	Bench	Mashiko (2015) [53]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	18	12 Neurosurgeons 6 Junior Neurosurgeons	1
Human Placenta Model: Intracranial Bypass (Placentarium, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil; Lyerly Neurosurgical Simulation Laboratory, Baptist Medical Cente, Florida, USA)	Human Tissue	Oliveira (2018) [59]	Content: 1 Response processes: N Internal structure: 2 Relations to other variables: 2 Consequences: N	60	5 Expert Neurosurgeons 5 Novice Neurosurgeons 50 Health Professionals	0
Venous Sinus Injury and Air Embolus Surgical Simulation (Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon)	Bench	Cleary (2018) [64]	Content: N Response processes: 1 Internal structure: N Relations to other variables: 1 Consequences: N	12	1 Attending Physician 11 Residents	1
ImmersiveTouch: Hemostasis Simulation (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Gasco (2013) [65]	Content: N Response processes: N Internal structure: N Relations to other	54	14 Residents 20 Senior Medical Students 20 Junior Medical Students	1

variables: N
Consequences: N

Table 4: Validation studies on training models for Non-Technical Skills & Spine Surgery. Abbreviations: LoE- Level of Effectiveness, VR- virtual reality

Model (Institution / Manufacturer)	Type of Model	Study	Validation	n	Participants Demographics	LoE
Non-Technical Skills						
Crisis Management Simulation: Dual Neurosurgery and Anaesthesia Training Experience (Anesthesiology and Perioperative Medicine, Oregon Health and Science University, Portland, Oregon, United States; Department of Neurosurgery, West Virginia University School of Medicine, Morgantown, West Virginia, United States)	Bench	Ciporen (2018) [105]	Content: N Response processes: N Internal structure: N Relations to other variables: 0 Consequences: N	14	7 Neurosurgery Residents 7 Anaesthesia Residents	1
Adult Cadaver Head Perfusion Model (Oregon Health & Science University Body Donation Program, Portland, Oregon)	Cadaver	Ciporen (2017) [49]	Content: N Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	6	Senior Residents	2
Task and Crisis Vertebroplasty Simulation (Technische Universitat Munchen, Munich, Germany)	VR	Wucherer (2014) [106]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	5	1 Expert Neurosurgeon 2 Senior Neurosurgeons 2 Junior Neurosurgeons	1
Spine Surgery						
Mixed Reality Spine Simulator (Paediatric Neurosurgery Center, Beneficencia Portuguesa Hospital, Sao Paulo, Brazil)	Bench/VR	Coelho (2018)[72]	Content: 2 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	16	Spine Surgeons	0
Durotomy Repair Module (Congress of Neurological Surgeons)	Bench	Ghobrial (2013) [67]	Content: N Response processes: N Internal structure: N Relations to other variables: N		1 Retired Neurosurgeon 4 Residents 1 Physician Assistant	2

			Consequences: N			
Congress of Neurological Surgeons Cervical Foraminotomy and Durotomy Repair Modules (Congress of Neurological Surgeons)	Bench	Ghobrial (2015) [68]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 0 Consequences: N	20	Residents	2
Microanastomosis, Anterior Cervical Discectomy and Fusion (ACDF), Posterior Cervical Fusion (PCF), and Durotomy Repair Modules (Congress of Neurological Surgeons)	Bench	Zammar (2015) [69]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	20	Residents	2
Low Cost Dural Closure Simulation Model (Department of Neurosurgery, Institute of Neurological Sciences, Glasgow, UK)	Bench	Ferguson (2018) [73]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	15	2 Spine Surgeons Fellows 13 Specialty Trainees	2
3D Software-based Pedicle Screw Simulator (Faculty of Medicine, Orthopaedic Biomechanics Laboratory, Sunnybrook Health Sciences Centre, Toronto, Ontario, Canada)	VR	Podolsky (2010) [74]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	37	Trainees	1
Simulated Lumbar Minimally Invasive Surgery Education Model (Department of Neurosurgery, Thomas Jefferson University Hospital, Philadelphia, Pennsylvania; Mayo Clinic, Rochester, Minnesota, USA)	Bench	Chitale (2013) [76]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	8	Trainees	2
Anterior Discectomy and Fusion Simulator (Congress of Neurological Surgeons)	Bench	Ray (2013) [70]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	6	1 Neurosurgeon 3 Residents 2 Medical Students	2
Cervical Spine Simulator (Congress of Neurological Surgeons)	Bench	Harrop (2013) [71]	Content: N Response processes: N Internal structure: N	11	1 Neurosurgeon 10 Trainees	2

			Relations to other variables: N Consequences: N			
Laboratory-based Spinal Fixation Training Program (Case Western Reserve University School of Medicine; Department of Neurological Surgery; Center for Spine Health, Neurological Institute, Cleveland, Ohio)	Bench/Cadaver	Sundar (2016) [77]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	10	8 Residents 2 Medical Students	2
Minimally Invasive Spine Surgery Simulator (Department of Neurosurgery, University of Mississippi Medical Center, Jackson, Mississippi, USA)	Bench/Animal	Walker (2009) [75]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	8	Residents	1
ImmersiveTouch: Percutaneous Spinal Needle Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Luciano (2013) [79]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	63	Fellows Residents	2
ImmersiveTouch: Thoracic Pedicle Screw Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Luciano (2011) [78]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	51	Fellows Residents	2
Saw Bones Scoliosis Model (Stony Brook University Hospital, Stony Brook, USA)	Bench	Tanner (2017) [80]	Content: N Response processes: 2 Internal structure: N Relations to other variables: 1 Consequences: N	20	10 Senior Residents 10 Junior Residents	0
Desktop-based Computer Assisted Orthopaedic Training System (Department of Computer Sciences, University of Hull, United Kingdom; Department of Orthopaedics, Leeds Teaching Hospital NHS Trust, Leeds, United Kingdom)	VR	Rambani (2014) [82]	Content: N Response processes: 2 Internal structure: 0 Relations to other variables: N Consequences: N	12	Junior Trainees	2
Life-Sized 3D Spine Model (Department of Orthopaedic Surgery, Kangnam Sacred Heart Hospital, Hallym University College of Medicine, Seoul, South	Bench	Park (2018) [83]	Content: N Response processes: N	2	Novice Surgeons	2

Korea)			Internal structure: N Relations to other variables: N Consequences: N			
Bioskills Training Module: Lumbar Pedicle Screw (Northwestern Memorial Hospital, Chicago, Illinois, USA)	Bench	Boody (2018) [84]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	19	Orthopaedic Residents Medical Students	2
Bioskills Training Module: Lumbar Laminectomy (Northwestern Memorial Hospital, Chicago, Illinois, USA)	Bench	Boody (2017)[85]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	20	Orthopaedic Residents Medical Students	2
Artificial Wetlab Training System for Lumbar Discectomy (Krankenhaus Winsen, Orthopadie, Winsen, Germany)	Bench	Adermann (2014) [86]	Content: 1 Response processes: 1 Internal structure: N Relations to other variables: N Consequences: N	12	Experienced Spine Surgeons	1
Cadaveric Spinal Surgery Simulation; Thiel, Crosado and formaldehyde (Health Education Yorkshire and the Humber, University of Leeds, Leeds, United Kingdom)	Cadaver	Tomlinson (2016) [87]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	10	Fellows Consultants	1
Virtual Surgical Training System (Department of Orthopaedic Surgery, Changzheng Hospital, Second Military Medical University, Shanghai, China)	VR	Hou (2018) [88]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	10	Novice Residents	2
ImmersiveTouch: Pedicle Screw Placement (ImmersiveTouch Inc., University of Illinois at Chicago Medical Center, Chicago, IL, USA)	VR	Gasco (2014)[81]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	26	Medical Students	2
3D Patient-Specific Rendering: Pedicle Screw Insertion (Department of	VR	Xiang (2015) [89]	Content: N	4	2 Experienced Spine	2

Orthopedics, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning, China)	Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	Surgeons 2 Junior Surgeons

Table 5: Validation studies on training models for Endoscopic Endonasal Transphenoidal Surgery . Abbreviations: LoE- Level of Effectiveness, VR- virtual reality.

Model (Institution / Manufacturer)	Type of Model	Study	Validation	n	Participants Demographics	LoE
Endoscopic Endonasal Drilling Model (Department of Learning Health Sciences, University of Michigan Medical School, Ann Arbor, Michigan, USA)	Bench	Tai (2016) [93]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	8	Neurosurgeons Residents	1
Chicken Eggs and Skull Model (Department of Neurosurgery, Kinki University Faculty of Medicine, Osaka, Japan)	Bench	Okuda (2014) [94]	Content: N Response processes: N Internal structure: N Relations to other variables: 2 Consequences: N	9	4 Experts 5 Residents	2
Laser Sintered Model (Ohio State University, Columbus, Ohio, USA)	Bench	Maza (2018) [50]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	46	20 Otolaryngologists 26 Neurosurgeons	2
Perfusion-Based Human Cadaveric Simulation for ICA injury (Keck School of Medicine, Los Angeles, California, United States)	Cadaver	Shen (2018) [52]	Content: N Response processes: N Internal structure: N Relations to other variables: 0 Consequences: N	35	19 Neurosurgeons 16 Otolaryngologists	2
	Cadaver	Pham (2014) [51]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	n/a	Residents	1
Practical 3D Printed Simulator (Department of Neurosurgery, Jinling Hospital, School of Medicine, Nanjing University, China)	Bench	Wen (2016) [95]	Content: N Response processes: N Internal structure: N Relations to other variables: 2 Consequences: N	23	5 Expert Neurosurgeons 7 Assistant Neurosurgeons 6 Novice	2

					Neurosurgeons 5 Trainees	
3D Endoscopic Skull base models w/ Pre-existing pathology (Division of Neurosurgery, Department of Surgery, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia)	Bench	Narayanan (2015) [96]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	15	ENT Surgeons	1
3D Cranial base model (Department of Neurological Surgery, The Ohio State University Wexner Medical Center, Columbus, Ohio, USA)	Bench	Muto (2017) [97]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	5	Trainees	1
NeuroTouch Simulator: Endoscopic Endonasal Module (CAE Healthcare, Montreal, Quebec, Canada)	VR	Thawani (2016) [98]	Content: N Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	6	Residents	5
3D Printed Skull base for Transnasal endoscopic Skull base Surgery (Beijing Neurosurgical Institute, Beijing Tiantan Hospital, Capital Medical University, Beijing, China)	Bench	Zheng (2018) [91]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	13	3 Neurosurgeons 10 Residents	1
Neuro-Endo-Trainer (NET) SkullBase-Task-GraspPickPlace (Centre for Biomedical Engineering, Indian Institute of Technology Delhi, New Delhi, India)	Bench	Singh (2016) [92]	Content: 0 Response processes: 1 Internal structure: N Relations to other variables: N Consequences: N	61	4 Expert Neurosurgeons 19 Novice Neurosurgeons 38 Residents	1
Perfusion-based Cadaveric Simulation Model: Endoscopic Endonasal CSF Leak Repair (Department of Neurological Surgery, Keck School of Medicine, University of Southern California, Los Angeles, California)	Cadaver	Christian (2018) [90]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	9	Residents	1
Skull Base Injectable Tumor Model (Macquarie Neurosurgery, Australian	Bench	Gagliardi	Content: 1	6	3 Residents	1

School of Advanced Medicine, Macquarie University, Sydney, Australia)		(2018)[38]	Response processes: N Internal structure: N Relations to other variables: N Consequences: N		3 Faculty Surgeons	
Adult Cadaver Head Perfusion Model (Oregon Health & Science University Body Donation Program, Portland, Oregon)	Cadaver	Ciporen (2017) [49]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	6	Senior Residents	2

Table 6: Validation studies on training models for Paediatric neurosurgery . Abbreviations: LoE- Level of Evidence, LoR- Level of Recommendation, VR- virtual reality.

Name of Model (Institution / Manufacturer)	Type of Model	Study (Year)	Validation	Participants n	Participants Demographics	LoE
'babyMARTYN' (Victor Horsley Department of Neurosurgery, National Hospital for Neurology and Neurosurgery, Queen Square)	Bench	Craven (2018) [100]	Content: 1 Response processes: 2 Internal structure: N Relations to other variables: N Consequences: N	11	3 Neurosurgeons 8 Trainees	2
SickKids brain simulator (Centre for Image Guided Innovation and Therapeutic Intervention, Toronto, Ontario, Canada)	Bench	Breimer (2015) [20]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	25	16 Residents 5 Fellows 4 Neurosurgeons	1
		Breimer (2017) [21]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	26	23 Residents 3 Fellows	1
NeuroTouch Simulator: ETV Module (CAE Healthcare, Montreal, Quebec, Canada)	VR	Breimer (2017) [21]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	26	23 Residents 3 Fellows	1
Full Scale Hydrocephalus Head Model (Harvard Medical School, Boston, Massachusetts and Division of Pediatric Neurosurgery, Johns Hopkins Hospital, Baltimore, Maryland, USA)	Bench	Weinstock (2017) [22]	Content: N Response processes: 2 Internal structure: 2 Relations to other	17	13 Residents 4 Fellows	1

			variables: 2 Consequences: N			
CURE Hydrocephalus and Spina Bifida Fellowship (CURE Childrens Hospital of Uganda, Mbale, Uganda)	Bench	Dewan (2018)[101]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: 2	33	Fellows	5
Synthetic Endoscope-assisted Craniosynostosis Models (Center for Image-Guided Innovation and Therapeutic Innovation, The Hospital for Sick Children, Toronto)	Bench	Eastwood (2018) [102]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	25	5 Expert 9 Fellows 11 Residents	1
Prototype for Pediatric Spinal Detethering Surgeries (University of Illinois ,College of Medicine at Peoria, Peoria, IL, USA)	Bench	Bailey (2013) [103]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	12	1 Neurosurgeon 1 Fellow 6 Residents 4 Students	1
3D Synthetic Model for Pediatric Lumbar Spine Pathologies (Department of Neurosurgery, University of Illinois College of Medicine, USA)	Bench	Mattei (2013) [104]	Content: N Response processes: N Internal structure: N Relations to other variables: 1 Consequences: N	7	3 Experts 1 Medical Student 3 Residents	0

Table 7: Validation studies on training models for Training Courses. Abbreviations: LoE- Level of Effectiveness, VR- virtual reality.

Model (Institution / Manufacturer)	Type of Model	Study	Validation	n	Participants Demographics	LoE
Training Courses						
National Fundamentals Curriculum (Society of Neurological Surgeons)	Bench	Selden (2012) [66]	Content: 2 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	261	75 Neurosurgeons 186 Residents	2
		Selden (2017) [99]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	164	Residents	3
Neurosurgery Boot Camp: Bolivia (Bolivian Society for Neurosurgery; Foundation for International Education in Neurological Surgery; Solidarity Bridge; University of Massachusetts)	Bench	Ament (2017) [23]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	29	5 Neurosurgeons 24 Residents	1
Fundamentals of Neurosurgery (Department of Neurology and Neurosurgery, Montreal Neurological Institute and Hospital, Brain Tumour Research Centre, McGill University, Montréal, Quebec, Canada)	VR	Choudhury (2013) [24]	Content: 1 Response processes: N Internal structure: N Relations to other variables: N Consequences: N	n/a	Subject Matter Experts	0
Trauma Module w/ ImmersiveTouch: Ventriculostomy (Congress of Neurological Surgeons)	VR	Schirmer (2013) [25]	Content: N Response processes: 1 Internal structure: N Relations to other variables: 2 Consequences: N	12	Residents	2
Trauma Module w/ Physical Craniotomy Model (Congress of Neurological Surgeons)	Bench	Lobel (2013) [109]	Content: N Response processes: N	14	Residents Medical Students	2

			Internal structure: N Relations to other variables: 1 Consequences: N			
SBNS-accredited Neurosurgical Skills Workshop (Society of British Neurological Surgeons; The Neurology and Neurosurgery Interest Group)	Bench	Kamel (2017) [107]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	10		2
Presigmoid Approach Simulation Module (Congress of Neurological Surgeons)	Bench	Jabbour (2013) [108]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	9	Residents	2
Simulation Curriculum (Division of Neurosurgery; and Division of Epidemiology & Biostatistics, University of Texas Medical Branch, Galveston, Texas, USA)	Bench/VR/ Cadaver	Gasco (2013) [110]	Content: N Response processes: N Internal structure: N Relations to other variables: N Consequences: N	130	Residents	1

Figure 1
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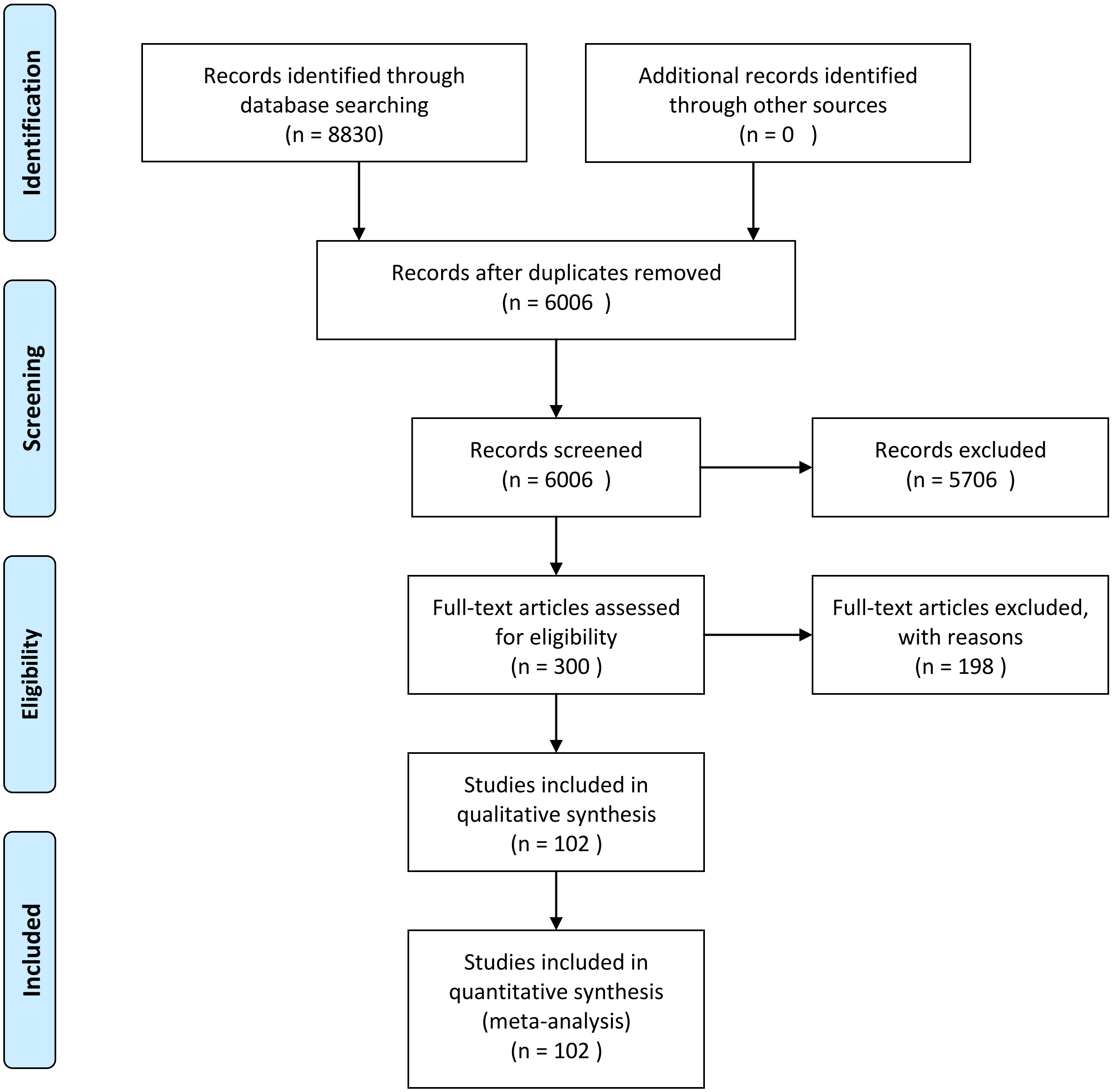
PRISMA 2009 Flow Diagram



From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *P*referred *R*eporting *I*tems for *S*ystematic Reviews and *M*eta-*A*nalyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

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Supplementary Tables 1-2

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